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16. Abstract

Arizona at present uses the AASHTO Interim Guide equations to determine thickness of structural layers (flexible and rigid) in the highway prism. Inputs to these equations are based on past experience and have been empirically developed. In the future Arizona intends to adopt a systems approach to design of both flexible and rigid pavements.

As such several inputs including traffic, environment, construction, structural and maintenance will be needed. The long term (3-5 years) objective of this study is to quantify the environmental inputs and relate them to highway performance. The purpose of this phase of the study was to develop, test and install the sensors and instrumentation to implement a program to monitor moisture and temperature changes in and under the highway.

The short term objective was accomplished thru the installation of monitoring equipment at 34 sites stratigically located about the state of Arizona. A schedule for collection of data (temperature, moisture and deflection) was established. Data collection via this schedule will continue into the future.

As data is collected it will be analyzed for future incorporation into the design, construction or maintenance operations.

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ACFC	Asphaltic Concrete Finishing Course
AC	Asphaltic Concrete
BMS*	Bituminous Mixed Surfacing Base materials mixed with asphalt. Mixed and placed with a blade.
BTB*	Bituminous Treated Base Base material mixed with asphalt in a hot plant.
BPM*	Bituminous Plant Mix Mineral aggregate mixed with asphalt. Old term for asphaltic concrete.
BSB*	Bituminous Stabilized Base Base material penetrated with ashalt.
CTB	Cement Treated Base Mineral aggregate or soil mixed with 4 to 5 percent cement.
AB	Aggregate Base Graded aggregate. Graded about the maximum density line.
SM	Select Material Aggregate composing the subbase layer. Not graded as closely as AB.
SGS	Subgrade Seal Generally sand. This material used to seal clay from pumping into subbase or base.
SS	Same as subgrade seal.
BORROW	Material found along alignment used to build embankment.

*Pre-1960 Terminology

N.G.	Natural Ground
℄	Centerline of Highway
LL	Liquid Limit from Atterburg Test
PL	Plastic Limit from Atterburg Test
PI	Plasticity Index
C	Cohesion Value from Shear Test
ϕ	Internal Friction Angle of Soil from Shear Test.
σ	Overburden Load Calculated from Wet Density of Layers
τ	Shear Strength of Soil

FINAL REPORT

HPR 1-12 (147)

Introduction

Arizona at present uses the AASHO Interim Guide (1) equations to determine thickness of structural layers (flexible and rigid) in the highway prism. Inputs to these equations are based on past experience and have been empirically developed. In the future Arizona intends to adopt a systems approach to design of both flexible and rigid pavements. Various systems for design and management have been proposed by Monismith, Hudson and Deacon (2), NCHRP 139 (3) and HRB Special Report 126 (4) to name a few. All of these systems call for several inputs including traffic, environment, construction structural capacity and maintenance schedule. The long term (3-5 years) objective of this study is to quantify the enviornmental inputs and relate them to structural characteristics. The purpose of this phase of the study was to develop, test and install the sensors and instrumentation to implement a program to monitor moisture and temperature changes occurring in an under the highway.

To perform the above task a general research plan was adopted. This plan involved the use of existing temperature and moisture measuring devices. A review of the literature indicated a need to distinctly monitor the moisture and temperature changes in the subgrade material, base and surfacing layers. As such, a two part program was adopted. One part of the research would concentrate on the moisture changes of subgrade materials. Past literature (5) indicated that the nuclear depth moisture probe was quite well suited for this purpose. Part two of this research involved the measurement of temperature and moisture in all structural layers down to the top one foot of subgrade. Previous literature (4), (6) had indicated that each structural layer down to subgrade could be greatly influenced by both moisture and temperature. Such influences indeed could even be expected on an hourly basis, therefore warranting a continuous recording type apparatus. A one channel strip chart recorder with a custom made timer and switching unit was selected to perform the continuous recording. Resistivity devices were chosen for measuring moisture and thermistors for temperature. The following text will recount the specific work done to accomplish the installation of the necessary equipment for both the nuclear depth moisture monitoring and daily recording of temperature and moisture in each structural layer down to subgrade.

Nuclear Moisture Measurement

The nuclear moisture measurement method has been in use for some time. Previous reports (5), (7), have documented the use of available equipment. The Haliburton report (5) in particular was followed quite closely in this study. The purpose of using the nuclear depth moisture equipment would be to study the long term moisture fluctuations of primarily subgrade materials two feet or more below the pavement surface.

Nuclear depth moisture probes were used in this study. Fast neutrons emitted by the radioactive source in the probe are moderated (thermalized) by the hydrogen in the soil moisture. Some of the thermalized neutrons reach the detector tube in the probe and are sensed, thus providing a measurement of in-situ moisture (5), (8). Both probes and scalers (Troxler Model 1255 Nuclear Depth Moisture Systems) (Figure 1) were provided with calibration curves supplied by the manufacturer. Tests by the Arizona Department of Transportation proved these curves to be substantially correct. The nuclear device, however, is subject to errors due to varying materials, density or chemical composition to name a few. Also boundry effects such as being too close to the surface and field installation can cause error.

With these restrictions in mind the nuclear probe appeared best suited for subgrade type deposits.

Site Selection

Twenty sites across the state were selected as nuclear moisture monitoring locations, Figure II. Sites were selected to represent a cross-section of materials and climate in Arizona. Subgrade materials included cemented sand and gravels, silts, clays and dessicated clays. Air temperatures range from summer highs of 110^{o}F or more in the southern desert to lows of -30^{o}F in the mountains during the winter. Rainfall varies from 4 inches to 25 inches. Both flexible and rigid pavements were selected as well as a few uncovered grade and drain locations. Some sites have irrigation on both sides of the highway. Since nuclear measurements need to be conducted out on the highway by trained personnel, traffic control became a major factor in site selection. All pavement sites are straight (one mile site distance), flat (less than 2% grade) and located on divided interstate highways. Table I gives the site location by the name of the nearest landmark, mile post number, station number and construction project number. Besides this some additional information is given. This includes the elevation in feet (Meters), nearest weather station, geology (12), topography, vegetation (13), drainage (14) and date built. Following site selection acquisition of materials began.

Nuclear Depth Moisture Installation

After purchasing necessary equipment installation began. At each site attempts were made to install four ten foot long, 2 inch outside diameter by 1.90 inch inside diameter class 150 aluminum tubes. Tube type and dimensions were suggested by the manufacturer of the nuclear depth moisture gauge (8). Tubes were to be installed in the shoulder or median, distress, travel and passing lanes at each site. In some cases it was not possible to install 10 foot long tubes in each position across the road. This was due to problems in drilling caused by rocks. Drilling through the pavement and base materials was accomplished by using a 6 inch auger with multi-purpose head driven by a B-30-SH Mobil Drill Rig. Beneath the base layers either a 2 inch or 4 inch auger was used. To determine whether a 2 inch or 4 inch auger should be used an exploratory 6 inch hole was drilled. For damp or wet fine material generally a 2 inch auger could be used. If rock was encountered during the exploratory drilling or the material was very dry a 4 inch Mobile Hex-Core auger with multi-purpose head was used. As drilling proceeded samples at 2 foot intervals beneath the base course were taken for nuclear gauge calibration. This sampling was accomplished by drilling two feet into subgrade then removing the auger. Sample material was removed off the auger and placed in two clean smooth sided 8 ounce tins. Each tin was marked and sealed with tape for future testing.

After the hole had been drilled to 10 feet or as deep as possible up to 10 feet, an aluminum tube of appropriate length was placed in the hole. Each tube was sealed at the bottom by using a 2 inch cork. The 2 inch auger holes generally gave a neat tight fit for the aluminum tubes. For 4 inch auger holes excess cuttings out of the hole at 2 foot intervals were stored in plastic bags and then poured around the tube and tamped in place. Tamping was accomplished by using a long 1/2 inch steel rod with a flat foot attached to the end. Material was dropped down the hole and tamped in place about the pipe. After tube placement a 4 inch diameter by 12 inch high sewer pipe cleanout was seated around the tube and grouted flush with the pavement. A brass cap neatly covered the hole. Figure 3 shows a diagrammatic representation of a typical access tube installation.

After tubes had been installed and cleanouts were in place, calibration using the nuclear probe began. Nuclear calibration was achieved by first taking a standard count. This generally involved about 20 one minute readings in order to achieve the manufacturers suggested reliability range. After standardization the nuclear probe was dropped down the tube 2 feet into the subgrade and three readings were taken. Readings were taken at 2 foot intervals under the base to the bottom of the tube (Figure 4). The average of the three readings were computed into volume percent moisture using the manufacturers calibration curve. These volume percent moistures were correlated to the sample oven dry moistures later obtained by test. It was assumed that the nuclear percent moisture would be zero at zero percent oven dry moisture. With these two points a straight line with the formula % moisture by weight = 0 + slope of line times % moisture by volume. This afforded an easy and accurate means of correlation. In addition, since the nuclear gauge measures percent moisture by volume drive samples were also taken to determine the moisture density relations of the subgrade material to a depth of 4 feet (1.219 meters). Drive sampling was accomplished by using a Dames and Moore Split Ring sampler (Figure 5). This device was driven with a 140 lb. drop hammer to a nominal depth of 18 inches (.4572 meters). From the samples two five ring (ring one inch high (.0254 meters) by two inch (.0508 meters) diameter) samples were recovered, placed in individual plastic bags and sealed inside fitted aluminum canisters for future laboratory testing.

Because of the flimsy nature of the two inch auger installation of nuclear sites was slower than expected. On numerous occasions the auger was bent or broken. Aluminum tubes needed to be thoroughly cleaned out and checked for dents before transport to a site. When thorough inspections were not made serious problems involving the hanging up of the dummy probe in the tube were encountered. Drive samples could only be taken when the soil was damp and had some cohesion. Dry, cohesionless soils generally fell out of the sampler.

Laboratory Testing

Samples taken during site installation were tested to determine moisture as well as various index and strength properties. The two eight ounce tins of soils taken at each two foot depths were oven dried to constant weight at 140°F (60° Celsius). This was done so that soils could be tested for Atterburg limits and grading. Tests performed included Arizona 204, 206, 207 (16) which are modifications of AASHTO T87, T89, T90 (17) respectively.

Drive samples taken at selected sites were used to determine wet and dry density. In addition where applicable a set of shear tests were run on the one inch high ring samples. Tests were run in a Soil Test constant strain direct shear device, Model D 120. Samples were run at their natural density and moisture. Surcharge loads of 784 Lbs/Ft^2 (37538.12 Pa), 1568 Lbs/Ft^2 (75076.25 Pa) and 2352 Lbs/Ft^2 (112,614.37 Pa) were used to perform the test. A constant shear rate of .099 inch/minute (.00003810 m/s) was applied and strains were measured using Ames dials. Readings were taken at every .010 inch (.00254 m) up to failure or .200 inch (.00580 m) whichever came first.

After testing was completed, data was accumulated and assembled into a final form. Figures 6 thru 26 contain all information derived for each site installation including site number, name and highway locations and date of test. A cross sectional view is shown of each site and thicknesses of each layer are drawn to scale. Cross slopes and tube locations in the cross section are actual locations. Oven dry moistures representing the average of two tests taken at two foot intervals are underlines. Dry densities are shown for each layer. Some of these densities are assumed, others were actually determined via the drive sample testing and are so marked. From these two values (dry density and moisture) degree of saturation could be determined by assuming an appropriate true specific gravity. As such a true specific gravity of 2.65 was used due to the silicious nature of the soil. In a few of the sites a 2.70 specific gravity was used to reflect the limestone aggregate present. Degree of saturation is shown in parentheses beside each moisture content. Also shown on the figures are results of tests for liquid limit, plastic limit, plasticity index as well as percent passing the 3/8, No. 4, No. 40 and 200 sieves. These values represent the average of three test results except where otherwise noted. Where shear tests were run results are shown as cohesion and friction values (C and ϕ). Overburden weights were calculated from the thickness and wet density of each layer.

Monitoring of Nuclear Sites

After all nuclear sites had been installed a monitoring program began. This program involved the nuclear determination of moisture at two foot depths once every other month. This schedule involves readings in January, March, May, June, August, October and December. In addition to moisture readings, deflection tests are also performed in the months of January, March, May, August and October.

The schedule of readings is intended to coincide with the climatic conditions generally typical of Arizona. That is:

January	Cold; wet or frozen dependent on location in State.
March	Cold; wet and thawing.
May	Warm; dry.
June	Hot; dry.
August	Hot; middle of monsoon rainy season.
October	Cool; dry.
December	Cool to cold; rain and snow.

Additional readings may be taken depending on the availability of the equipment. Roughness values as measured by the Mays Meter are obtained once a year as a part of Arizona's annual pavement evaluation program (18). Initial values for each site are shown on Table II. Besides these performance tests, samples (cores) of asphaltic concrete (AC) were taken for physical and chemical tests. Typical tests on AC include bulk density, voids analysis, viscosity and Rostler analysis as per Arizona Report 4 (20). Cores are being tested by the University of Arizona for elastic modulus values (19).

Continuous Monitoring of Moisture and Temperature Recording Sites

Moisture monitoring was intended to reflect the changes in moisture from surfacing to subgrade. Unfortunately changes in surface moisture or base layer moisture cannot be measured with accuracy with the nuclear depth moisture gauge due to geometrical (layer thickness) constraints. In addition to this moisture changes in the upper layers of the highway structure probably change very rapidly with rainfall. Therefore some continuous moisture measurement method was needed for the upper part of the pavement structure. The moisture monitoring system selected for those layers from top of subgrade to surfacing involved the use of sensors compatable with recording equipment. The intended system would involve placement of temperature and moisture sensors in the wheel path of the travel lane at selected locations. Sensors would be connected to suitable timing and recording equipment to allow the recording of each sensor once every four hours. Recorded data would be converted to punch cards for computer conversion into temperature and moisture values.

Equipment Selection

Before any temperature or moisture sensors were purchased a cursory literature review was performed. This review indicated several sensors were commercially available.

The reviewed literature advised use of either thermocouples or thermistors to measure temperature. Both sensors were tested with available highway department instrumentation. For this study thermistors were selected to measure temperature. Other researchers (9), (10) had indicated good success with thermistors. These devices are economical, durable and easily interfaced with common recording equipment. Thermistors selected for this study were disk type Fenwal Electronics Model JA41J1.

These thermistors were soldered to 25 foot leads. Soldered joints and thermistors were encased in epoxy to protect them from damage as well as shorting.

The literature review (11) advised use of several different sensors including gypsum blocks or fiberglass blocks. Both these devices were tested in this study and later used at actual moisture monitoring sites.

Fiberglass blocks used were from Soil Test #MC-314 and the

Gypsum blocks were as provided by Beckman Instrument, Inc. Both devices work on a resistivity principle; that is the materials specific conductive capacity and its dielectric losses vary with the amount of moisture it contains. Devices come with five foot leads and it was necessary to extend the leads to 25 feet with a soldered joint. Soldered joints were coated with sealer and taped over with electrical tape. The instrumentation finally arrived at involved use of an inexpensive, rugged, accurate one channel strip chart recorder Rustrak Model 288 and a small inexpensive custom made timer and switching unit. The recorder is a model 288, 0-10 millivolt and holds 63 feet of chart paper. The paper is driven at one foot per hour or about 3/8" per each two minute channel.

The timer switching unit is designed to allow 0-6 volt DC excitation for the thermistor. In order to properly excite and read the moisture gauge a square wave signal of one hertz was necessary. Such a signal is generated in the timer. The amplitude is variable and can be set from 0-12 volts peak to peak. Besides the excitation the timer would need to turn on the recorder once every four hours and pole 16 channels (8 DC and 8 AC) for two minutes each. All of these design features were achieved for a nominal price. Total cost of both the recorder and timer amounted to approximately \$370. Wiring diagrams of the recorder and timer units are shown in Figures 27 and 28.

Initial Field Installation

While work on the construction of timers continued, recording sites were selected. These sites were selected to represent the different materials and climates in Arizona. In addition an urban curb and gutter and irrigation section were included. Due to the need for power, available traffic counting locations were selected. These locations offered not only power but also hourly traffic counts. Figure 29 shows locations of recording sites in Arizona. Table III gives the site location by name of the nearest landmark or city, milepost number and station number used in construction, noted construction project. Additional information includes elevation, nearest weather station, geology (12), topography, vegetation (13), drainage (14) and date built.

Following site selection work on initial field installation could begin. This initial work was aimed at preparing the site for the future installation of sensors and recording equipment. Sensors and recording equipment would be placed following moisture sensor calibration performed with material sampled from the recording site.

At each site a traffic control cabinet was mounted on a power pole and electrical outlets installed inside the cabinet. A one foot wide trench was dug from power pole to the roadside. This distance averaged 70 feet. Likewise, a 6 inch trench was cut in the pavement out into the travel lane right wheel path. A two inch PVC conduit with a 23 twisted pair Belden cable was placed in the trench from the cabinet to the roadside. At or near the roadside a concrete pull box was installed to protect the cable connections. From the pull box the two inch PVC conduit was placed in the prepared trench in the highway. No sensors or wires were placed in the conduit at this time. For now the conduit was plugged and covered with AC cold patch which was compacted in place. In some cases two conduits were placed in the highway, this was done to accomodate any additional instrumentation at some future time. Figure 30 shows a typical recording site installation. After all trenches had been filled and compacted an additional three foot square hole was made in the travel lane. This hole or pit was used to perform an in-place density test. A volumeter moisture-density test (Ariz. Test 231a, modification of AASHTO T 205) was performed on each layer of material under the pavement to a maximum depth of 30 inches. Due to hole size limitation, 30 inches was as deep as was practical. Samples were taken from each layer and tested for grading Atterburg Limits and moisture content (Ariz. Tests 201, 202, 203, 204, 205, 206, 207 tests are modifications of AASHTO T27, T11, T87, T89, T90). Additional sample material from each layer was taken for purposes of moisture sensor calibration. Figures 31 - 43 show site cross section and test results.

Laboratory Calibration

Moisture sensor calibration involved use of soil samples taken from each site during conduit placement. Soil samples were oven dried and placed in one gallon cement cans. Distilled water was added to the dried soil, to bring the moisture content to three percent moisture. Moisture sensors were then placed in the wet soil, Figure 42. Wires were run through the lids of the can and sealed. The sensors were allowed 24 hours to equilibrate. After 24 hours the sensors were attached to the timer and recorder. Readings were taken at 2, 4 and 6 volts RMS AC. Moisture was added at two percent increments to the soil. In many cases it was necessary to thoroughly mix the soil and water in order to achieve uniform distribution. Readings were taken and recorded as before until saturation. Readings were plotted on linear paper with percent moisture versus chart reading. Typically these curves were of a half power shape (Figure 43). For very rocky materials and cinders, curves took on unusual shapes. This was probably due to problems in contact between sensor and soil. That is, if contact could not be achieved the moisture sensor became a humidity device and in so doing lost much of its resolution. The gypsum blocks were tried on several soils and generally found incompatible with the instrumentation. Gypsum blocks acted like sponges when placed in the presence of any free water. Indeed in several soils only 3 percent moisture was necessary to eliminate the resolution of the sensor. Fiberglass sensors generally gave good resolution over a large moisture range. Indeed fiberglass sensors responded so much better than the gypsum that gypsum blocks were placed at very few sites.

Calibration of thermistors involved use of epoxy encased devices attached to 25 foot leads. Leads were attached to the timer and the DC voltage adjusted to 2, 4 or 6 volts. Thermistors were placed in a constant temperature bath Forma Scientific Model #2095 ($\pm$ .02^{o}C) 35 - 120^{o}F. The bath was set to five different temperatures and the millivolt output recorded in terms of divisions of chart period. Temperature versus division of chart paper were plotted on log log paper to give a straight line, Figure 44. A computer best fit regression line using a Wang Model 700A was computed. Such regression lines were used to extrapolate lines for in between voltages. In most instances three separate voltages were not needed due to linearity of the devices. After thermistor calibration, devices were logged and set aside for future use in the field.

Final Installation of Equipment

After calibration for temperature and moisture was completed work on final installation of recording sites began. This work involved coring a hole in the roadway at the end of the conduit. Moisture and temperature sensors previously calibrated and marked were placed in each layer beneath the pavement. Moisture sensors were stored and placed at a moisture consistent with previous test results on samples taken at each site. By doing this, errors in calibration due to different materials could be reduced. As sensors were placed, soil was carefully backfilled about them and tamped in place. Lead wires were straightened and taped into a braid. The braid was fished through the conduit to a previously installed pull box. Lead wires were paired with the 23 pair cable and color chart of sensors of timer constructed. Wires were connected with a physical quick connect and coated with a sealer to prevent shorting. In the cabinet all 16 channels were connected to the timer. AC and DC voltages were set at appropriate excitations in order to get maximum resolution. Recordings were checked frequently during the first few days. Generally if problems occured in timing or recording they occurred very early in operations. Once all devices were functioning properly the recording operation was continued for a three week period.

Three week tapes were brought back from the recording site and coded. Coded information was stored in punch card form for future run through the computer and decoding into temperature and moistures.

Besides measuring temperature and moisture, performance tests are also performed at each site. These tests include Mays Meter (roughness) and Mu-Meter (skid resistance) once a year. In addition dynaflect readings are taken in January, March, May, August and October. Values from these tests are shown in Table VI.

In general installation of recorder sites were slowed by need to design and build a suitable timing device. Actual field installation was slowed by logistics of each recording site.

General Discussion of Overall Project

In summary, it should be remembered the purpose of this study was to develop, test and install the sensors and instrumentation to monitor temperature and moisture over a long period of time. This project has substantially accomplished the above task. In all 21 nuclear depth moisture sites and 13 daily recording sites have been built and are functioning.

In addition valuable material characteristic information was obtained from each site.

Future Research

Monitoring of all sites will continue as per the reported schedule as stated above. Sites will be used in cooperative research aimed at the long term objective. In addition to all this work other physical properties will be monitored on a selected basis. This includes pore pressure, stress and strain at selected sites.

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Implementation

All the work performed and results obtained from this study are part of a larger program aimed at determining the valuable information necessary for the design and rehabilitation of pavements in Arizona. This large program includes testing of cores taken at selected sites. Cores are tested for fatigue and E modulus values. Testing is being performed by Dr. Jimenez as part of his project "Structural Design of Asphalt Pavements" HPR 1-12 (142). Dynaflect readings are also being supplied to Dr. Jimenez as part of this project. Research on AC design will be complimented by future research at selected sites which will involve testing of the highway structure and subgrade materials via use of plate bearing and Mennard pressuremeter. This work will be done through another HPR study. All of this work at selected sites as well as site information is aimed toward utilization in a pavement management system.

The techniques and skills involved in installing and monitoring nuclear and recording sites has in the course of the past year been utilized in other research projects. These projects included a pre-construction study of use of electro-osmosis, and an HPR electro-osmosis study (HPR 1-11 (142)). Both these studies utilized the nuclear depth moisture equipment. In the future recording equipment will provide information on depth of freezing in northern Arizona.

REFERENCES

1. "AASHO Interim Guide for Design of Pavement Structures 1972".
2. "Structural Design of Asphaltic Concrete Pavements to Prevent Fatigue Cracking", Highway Research Board Special Report 140, 1973.
3. "Flexible Pavement Design and Management Systems Formulation", Hudson, W.R. and McCullough, B.F., Materials Research and Development, Inc., NCHRP 139, 1973.
4. "Structural Design of Asphalt Concrete Pavement Systems", Proceedings of a Workshop Held December 7-10, 1970, Austin, Texas, HRB Special Report 126.
5. "Subgrade Moisture Variations", Haliburton, T. Allan, Oklahoma Research Program, Project 64-01-3, August 1970.
6. "Theoretical Evaluation of the Effect of Temperature on the Fatigue Behavior of Bituminous Road-Bases", Nunn, M.E., Transport and Road Research Laboratory Department of the Environment, TRRL Report LR 594.
7. "The Nuclear Method of Soil-Moisture Determination at Depth", Ehlers, Clarence J., et al, Texas University, Austin, Texas, June 1969, PB 194-749.
8. "Instruction Manual Depth Moisture Gauge", Troxler Electronic Laboratories, Inc., Raleigh, North Carolina.

9. "Temperature Instrumentation for Indiana's Thermally Insulated Test Road", Walsh, H.R.J., Highway Research Record Number 429, 1973.

10. "The Response of Asphalt Pavements to Low Temperature Climatic Environments", Christison, J.T. and Anderson, K.O., Third International Conference on the Structural Design of Asphalt Pavements, Volume I, Proceedings 1972.

11. "Instrumentation for Measurement of Moisture", Ballard, L.F., NCHRP 138, 1973.

12. "Arizona Materials Inventory" for each county in Arizona, Arizona Highway Department, Materials Division.

13. "Southwestern Trees, A Guide to the Native Species of New Mexico and Arizona" Agriculture Handbook Number 9, U.S.D.A. Forest Service by Little, Elbert L., Dec. 1950.

14. "Hydrologic Design for Highway Drainage in Arizona", Arizona Highway Department, Bridge Division by Jencsok, Eugene I., March 1969, Page 44a.

15. "Arizona Climate 1931-1972", by Sellers, William D. and Richard H. Hill, The University of Arizona Press, Tucson, Arizona.

16. "Materials Testing Manual", Arizona Department of Transportation

17. "Highway Materials, Part II, Tests", AASHTO.

18. "Proceedings of the Eleventh Paving Conference", The University of New Mexico, Pavement Evaluation in Arizona, by Allen, G.J., January 10-11, 1974.

19. "Structural Design of Asphalt Pavement", by Jimenez, R.A., Arizona Highway Department, AHD-RD-10-142, May 1973.

20. "Asphalt Cement Durability and Aggregate Interaction", Rowan J. Peters, Arizona Highway Department, Research Report 4, April 1973.